ENERGY MONITOR FOR F_2 MOLECULAR FLUORINE LASER AND METHOD OF ENERGY STABILIZATION

5   This application claims the benefit of U.S. Provisional Application No. 60/122,145, filed February 26, 1999, and entitled <u>Energy Monitor For F_2-Excimer Laser And Method Of Energy Stabilization</u>.

FIELD OF THE INVENTION

10   The present invention relates to laser operation detection, and more particularly to an energy monitor and method for an F_2 molecular fluorine laser system.

BACKGROUND OF THE INVENTION

15   The present invention relates primarily to the field of industrial molecular fluorine (F_2) lasers and the application of F_2 lasers in optical lithography, annealing, micro machining, photo-ablation and others. Excimer lasers that are widely used today for these applications include XeCl lasers (308nm), KrF lasers (248nm), and ArF lasers (193mn). However, in the near future, F_2 lasers (157nm) will be more widely used based on their very short wavelength,

20   particularly for such applications as sub-0.18 micron photolithography. The short wavelength photon emission is advantageous for photolithography applications because the critical dimension (CD), which represents the smallest resolvable feature size producible using photolithography, is proportional to the wavelength. The smaller CD permits smaller and faster microprocessors and larger capacity DRAMs in a smaller package. The high 7.9 eV

25   photon emission energy at this low wavelength is also readily absorbed in high band gap materials like quartz, synthetic quartz (SiO_2), Teflon (PTFE), and silicone, among others, such that the F_2 laser has great potential in a wide variety of material processing applications.

Significant improvements are being made in the development of the F_2 laser to achieve an enhanced gain, longer pulse lengths, better pulse-to-pulse stability, and increased

30   lifetime. Some of these improvements are described in U.S. patent application nos. 09/343,333, 09/317,526, 09/317,527, 09/317,695, and 60/140,530, each of which is assigned to the same assignee and is hereby incorporated by reference into the present application.

For many industrial and laboratory applications, excimer and molecular fluorine (F_2) lasers are used in an operating mode that actively regulates and stabilizes the output power of

35   the laser to a preset, configurable power or energy level. The active stabilization typically

involves an energy detector that is connected to a control component for driving the high

voltage that excites the F_2 gas and for operating a gas control system. Accordingly, the

driving voltage and gas injections/replenishments are actively adjusted to stabilize the output

energy. This is possible because the output energy value depends on the input high voltage

5   and the precise gas mixture in the laser tube. Thus, a variation of output energy may be

compensated by adjusting the high voltage and/or laser gas mixture. See U.S. patent

applications no. 09/379,034, 60/123,928 and 60/124,785 (describing techniques for

compensating output energy variations based on halogen depletion including gas

replenishment, as well as high voltage adjustments over limited voltage ranges), each of

10   which is assigned to the same assignee as the present invention and which is hereby

incorporated by reference into the present application. Fast reliable energy monitors are very

important basic modules for the required pulse energy control of the excimer lasers. Most

applications of the 193 nm ArF and 248 KrF excimer lasers in optical lithography require

energy dose control with high precision pulse-to-pulse regulation.

15   There are other parameters of the output beam of an excimer laser that require

monitoring for various reasons. Among these output beam parameters are beam profile,

bandwidth, wavelength, energy stability, pulse shape and pulse duration. In particular, it is

desired to monitor any of these parameters in order to provide a feedback mechanism for

controlling the laser during operation, particularly when the output beam is being used for

20   precise industrial processing applications such as photolithography of small structures.

The UV laser radiation around 157 nm of the F_2-molecule has been observed as being

accompanied by further laser radiation output in the red region of the visible spectrum. This

visible light originates from the excited fluorine atom (atomic transition). It is desired to

have an F_2-laser wherein the parameters of the UV (157 nm) portion of the output beam, and

25   in particular the energy, may be monitored without substantial interference due to the

accompanying red emission spectrum of the laser.

With the trend of providing lasers with lower and lower wavelengths, monitoring of

the output energy, pulse length etc. is increasingly problematic, especially with those laser

systems that include visible and/or infrared light accompanying the primary UV output.

30   More specifically, silicon photodiodes have commonly been used as a reliable fast energy

monitor for excimer lasers (sometimes with enhanced UV sensitivity or covered by phosphor

coatings which down-convert the UV-radiation to the more sensitive visible spectral region of

these Si-photodiodes). However, Si-photodiodes have a low spectral response to UV light,

while having a significantly higher spectral response to visible and infrared light. Therefore

any visible or infrared component in the laser output disproportionately affects the measured output value. This is especially problematic for the F_2-laser, which includes red emission between 620 to 760 nm. Another problem with Si-photodiodes is that they degrade quite quickly when exposed to strong UV radiation, which is necessary to achieve a suitable

5   detection level in this region of low detectivity.

Attempts have been made to selectively suppress certain wavelengths emitted from the discharge of the laser tube, especially the parasitic red/infrared laser light of the F_2-laser. Because of the lack of suitable cut-off coatings or filters to separate the red radiation from UV on a single pass, a multi-pass beam delivery system has been designed. However, the

10   beam path is very sensitive to mirror misalignment and degradation of the coatings of the many optical beam steering mirrors. Gratings have also been employed to separate red radiation from UV, but again with limited success.

Other types of detectors have been used for UV detection, with limited success. For example, vacuum photodiodes have been employed to measure the UV laser output.

15   However, vacuum photodiodes tend to be cumbersome and expensive, and possess aging sensitive cathode layers. Even if special expensive materials are selected for coating the cathode to match the electron liberation energy to the quantum energy of the photons, they require a high vacuum and high voltage to operate, and therefore are not convenient for electronic signal processing on TTL voltage levels. Thermopiles can easily measure low UV

20   output, but are not fast enough for single pulse detection at high repetition rates.

There is a need for a suitable fast energy detector that is capable of detecting single pulse energies at 157 nm without being adversely affected by associated red radiation, and which is fast enough to permit energy regulation at higher repetition rates without premature degradation due to UV exposure.

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SUMMARY OF THE INVENTION

The present invention solves the aforementioned problems by providing an F_2 laser system that utilizes a photo diamond detector that measures only the UV radiation in the laser beam. The photo diamond detector is fast enough to measure high pulse energies beyond

30   1KHz, without premature degradation from the UV exposure.

The F_2 laser system of the present invention includes a molecular fluorine (F_2) gain medium disposed in a resonant cavity, a power supply for exciting the gain medium to produce a laser beam having an ultra violet (UV) radiation output at substantially 157 nm and a red radiation output in a 620 to 760 nm wavelength range, and a photo diamond detector

that receives a portion of the laser beam for measuring at least one optical parameter of the UV radiation. The photo diamond detector is substantially insensitive to the red radiation output in the laser beam.

In another aspect of the present invention, a method of operating an F_2 molecular fluorine laser system having a gain medium disposed in a resonant cavity comprises the steps of exciting a molecular fluorine gain medium to produce a laser beam having an ultra violet (UV) radiation output at substantially 157 nm and a red radiation output in a 620 to 760 nm wavelength range, directing a portion of the laser beam to a photo diamond detector, and measuring at least one optical parameter of the UV radiation using the photo diamond detector. The photo diamond detector is substantially insensitive to the red radiation output in the laser beam.

Other objects and features of the present invention will become apparent by a review of the specification, claims and appended figures.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is an optical/electrical schematic diagram of the F_2 molecular fluorine laser according to the present invention.

Fig. 2 is a side cross-sectional view of the photo diamond detector assembly of the present invention.

Fig. 3 is graph illustrating the spectral response of a photo diamond detector and a UV enhanced silicon detector.

Fig. 4 is a graph illustrating the 157 nm F_2 laser pulse shape as measured by the photo diamond detector of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention is an F_2 molecular fluorine laser system 1 that includes a UV sensitive photo diamond detector for active laser system energy detection, regulation and stabilization.

The F_2 laser system 1 is illustrated in Fig. 1, and includes a power supply 10 that excites a molecular fluorine gaseous gain medium within a laser tube 12 to produce a laser beam 14 oscillating inside a resonant cavity (defined by a high reflecting mirror 16 and an output coupling mirror 18). A portion of the oscillating laser beam 14 passes through the output coupling mirror 18 to form an output beam 22 which primarily contains 157 nm radiation but also includes red radiation between 620 to 760 nm as well. A discharge module

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20, which is well known in the art, provides the desired pressure and mixture of gases in the laser tube 12 through periodic gas injections and venting. A small portion of the output beam 22 is redirected by a beam splitter 24 to a photo diamond detector assembly 26, which measures various optical parameters of the output beam 22, such as power, pulse energy,

5   energy dose, pulse width, pulse shape, etc. The photo diamond detector assembly 26 has an output connected to a signal processing unit 28, which in turn is connected to a controller 29 ` that controls the operation of power supply 10 and discharge module 20 in response to the detected output beam parameters measured by the photo diamond detector assembly 26. Signal processing unit 28 and controller 29 are well known in the art for use with silicon

10   detectors, and therefore are not further described in detail here.

The 157 nm UV output is highly absorbed by the atmosphere. Therefore, the output beam 22 is hermetically sealed in a beam enclosure 30 that is purged with an inert gas. Metal bellows 31 also preserve the hermetic seal of the enclosure 30, as well as sealing the mirrors 16/18 to the laser tube 12. The beam splitter 24 is preferably made of an uncoated CaF_2

15   plate, which directs approximately 10% of the output beam 22 to the photo diamond detector assembly 26.

The photo diamond detector assembly 26 of the present invention is best illustrated in Fig. 2, and includes a photo diamond detector 32 mounted inside a sealed housing 34 having various aluminum metal housing parts 36, 38, 40 and seals 42, 44, 46. A stainless steel mesh

20   48 is mounted over the entrance face of the detector 32 to prevent any EMI disturbance of the detector signal (Faraday cage). The metal mesh 48 can have different mesh wire densities to selectively adjust the transmitted energy. A diffusor plate 50, preferably a scattering CaF_2-plate, is also mounted on the entrance face of the detector 10 to diffuse the incoming light, which minimizes beam movement and profile effects on the measured output. Other

25   scattering plates that can be used include plates made from MgF_2, quartz or fused silica, and graded LiF. The photo diamond detector 32 is electrically connected to a twin BNC-plug 52 for coupling the signal from detector 32 out of sealed housing 34 and to the signal processing unit 28.

The photo diamond detector 32 is a photosensitive resistor which is based on the

30   internal photovoltaic effect (i.e. the electron transition between the valence and conduction bands of diamond). Because the bandgap of highly pure crystalline diamond (which is a typical dielectric material) is very large (e.g. > 5.5 eV), only photons in the UV range can generate this quantum transition. Therefore the photo diamond detector 32 is naturally solar-blind, which means it is basically insensitive for wavelengths greater than about 225 nm. In

the preferred embodiment, a specially designed but commercially available diamond UV

photo detector from Centronic Ltd. is used. The full sensitivity in the short UV wavelength

region is presently not precisely known and is still under investigation. Fig. 3 illustrates the

known spectral response of a diamond photosensitive resistor, compared to that of a UV

5   enhanced silicon photodiode. It has been experimentally confirmed that the photo diamond

detector still works well at 157 nm wavelength exposure and generates a usable high signal

level of over a hundred mV at energy levels below 0.1 mJ or even 0.001 mJ. It was

previously unknown whether a diamond based detector would exhibit enough sensitivity and

fast enough response time at this low a wavelength.

10   By using photo diamond detector 32, no special sophisticated means are necessary to

suppress the red laser emission which accompanies the 157 nm UV radiation. Thus, a simple

beam delivery system can used, and energy monitoring is very convenient and adaptable to

regulate and stabilize the operation of the 157 nm F_2 laser at a desired pulse energy level.

There are many other advantages of using a photo diamond detector, such as its low

15   thermal sensitivity caused by the very low degree of intrinsic traps. The high damage

threshold of this material is relatively high ($\sim$ 1 GW/cm2 at 338 nm). It is also expected that

the long term stability of these kinds of photo detectors is orders of magnitude greater than

that of common Si-photodiodes or biplanar vacuum photodiodes for 157 nm exposure (even

enduring over 1.5 billion laser shots). Because of the photo diamond detector's high thermal

20   conductivity of 20 W/cm K and the very thin photo diamond plates, it is expected that this

energy monitor can tolerate high average power levels and therefore would be usable for high

repetition rate 157 nm pulse detection. It has been experimentally confirmed that the photo

diamond detector can operate at least up to a repetition rate of 1 kHz. Moreover, the linearity

of the photo diamond detector is quite good, which is important for a high resolution energy

25   monitor. Even more surprising was the discovery that the response time of the photo

diamond detector at 157 nm is much shorter than formerly assumed. Applying the photo

diamond detector for direct waveform detection of the 157 nm pulse via oscilloscope has

shown its capability to resolve the laser pulse shape and even the internal structure of the 157

nm pulse. Thus the time constant of the detector should be less than 5 ns for laser pulse

30   exposure under 157 nm. The diamond thin-film photo resistor has negligible thermal noise.

The dark current is at least smaller by a factor of 10^{-6} as compared to the signal at normal

room temperature because of the large intrinsic bandgap of diamond. Even more, it is

expected that the long-term reliability of the diamond photo resistor is much higher than that

of common Si-photodiodes for 157 nm exposure. The photo diamond detector can be used within a vacuum level down to 10^{-6} mbar.

Fig. 4 illustrates the 157 nm F_2-laser pulse shape as measured by a photo diamond detector and oscilloscope with high time resolution (20 ns/division, 200 mV/div). The
5   waveform is detected at a laser repetition rate of 1 kHz. This demonstrates the unexpected and very surprising result that the photo diamond detector at 157 nm has a very short time constant. The short time constant allows a real time registration of the 157 nm-waveform at suitable high voltage levels with resolution of less than 5 ns (as seen by the resolution of single roundtrips within the waveform).

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It is to be understood that the present invention is not limited to the sole embodiment described above and illustrated herein, but encompasses any and all variations falling within the scope of the appended claims. For example, the photo diamond detector could sample a portion of the intracavity laser beam oscillating inside the resonant cavity instead of the
15   output beam exiting from the resonant cavity. Further, controller 29 can be a separate single unit as shown in Fig. 1, or separate components integrally part of power supply 10 and discharge module 20.

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